Superconducting Nanowire Single Photon Detectors

for **Deep Space Optical Communications**

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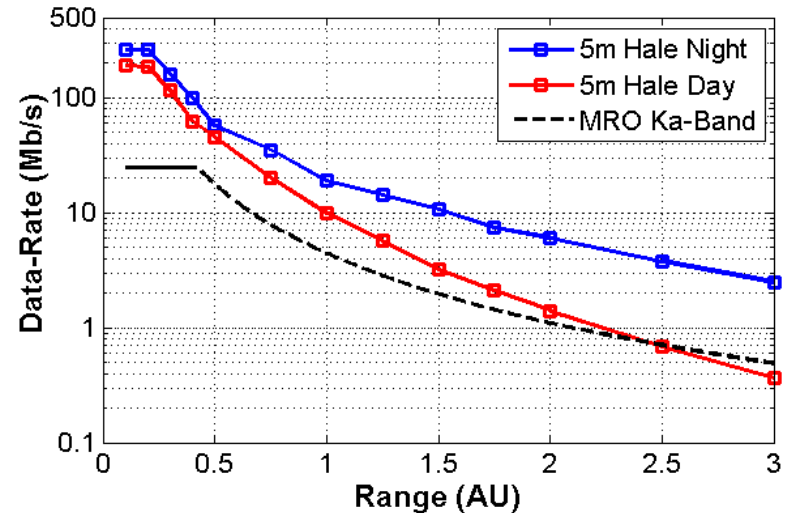
[1]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*
[2] *Dotfast Consulting, Kufstein, Austria*

Jet Propulsion Laboratory
California Institute of Technology

Why deep space optical communication?

DSN antenna at Goldstone, CA

Performance using 4W average laser power w/ 22 cm flight transceiver to 5m ground telescope

- **Currently:** Radio frequencies up to 40 GHz through the Deep Space Network (DSN)
- Future "optical DSN" promises **10-100x** more data than Ka-band RF links for equivalent mass and power on the spacecraft
- Will require larger (~ 10m) telescopes than current and past technology demonstration missions
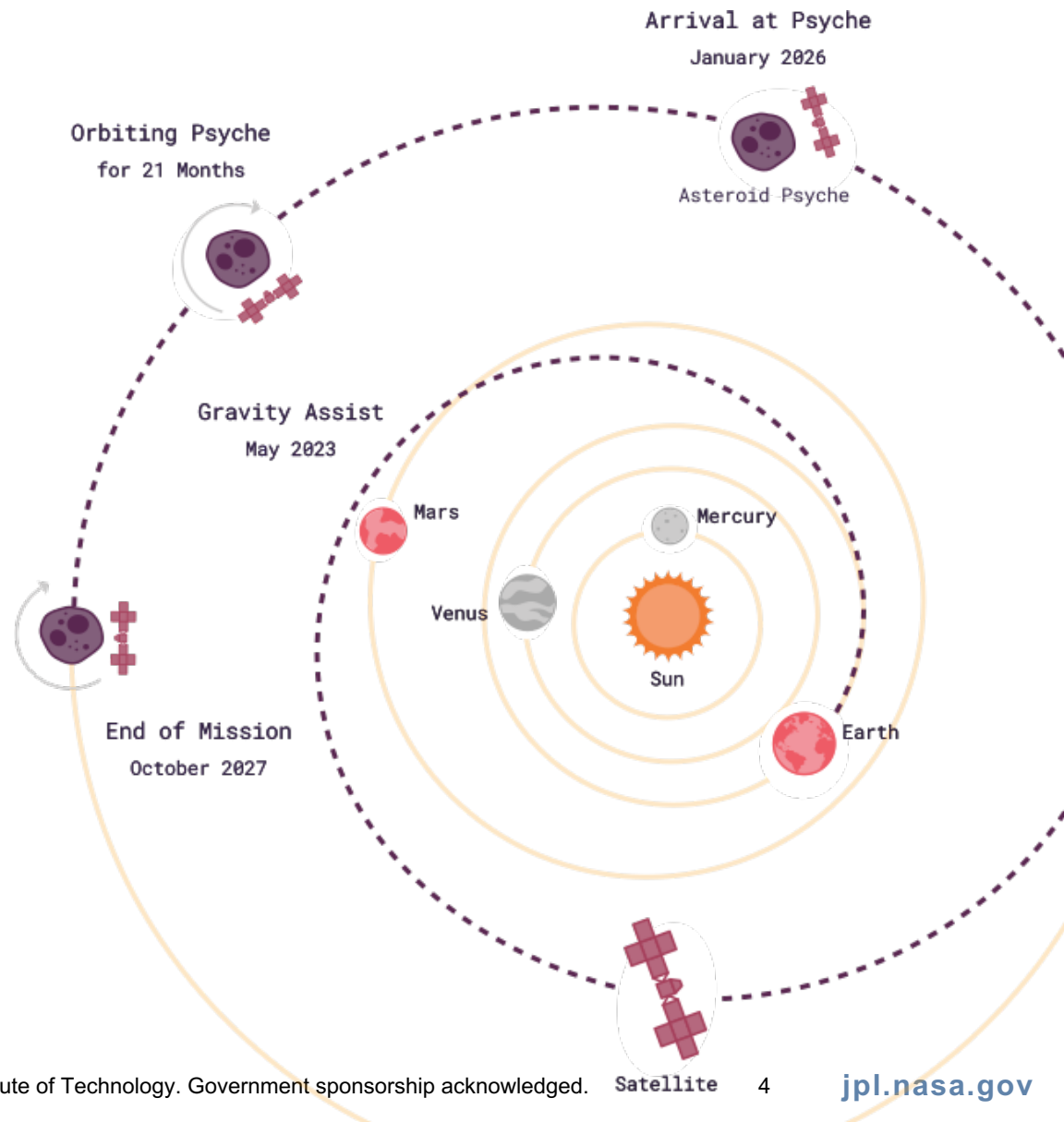
Lunar Laser Communication Demo (2013)
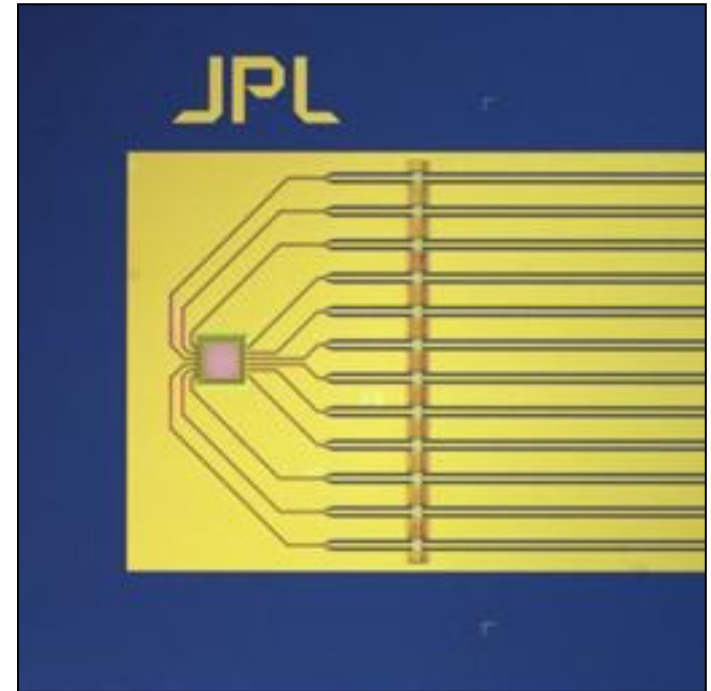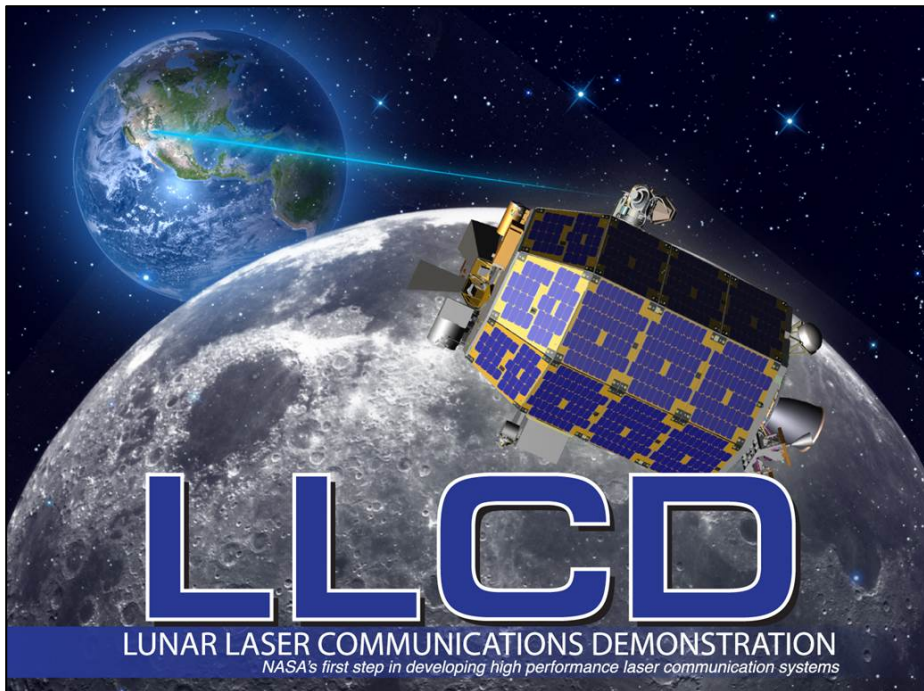
- Bidirectional laser communication demo from lunar orbit (400,000 km) at 1550 nm
- First demonstration of laser communication beyond earth orbit
- Uplink rates 10-20 Mbps, Downlink rates 39-622 Mbps
- Transmit Payload on LADEE Spacecraft (ARC) implemented by MIT-LL
- Managed by GSFC, Primary ground terminal implemented by MIT-LL using NbN SNSPD arrays
- Secondary ground terminal implemented by JPL using a WSi SNSPD array

Deep space optical communication (DSOC) project

- DSOC is a technology demonstration mission planned to launch on board NASA's Psyche mission in 2022

- Psyche's trajectory takes it past Mars to the asteroid belt, where it will study the metal asteroid 16 Psyche

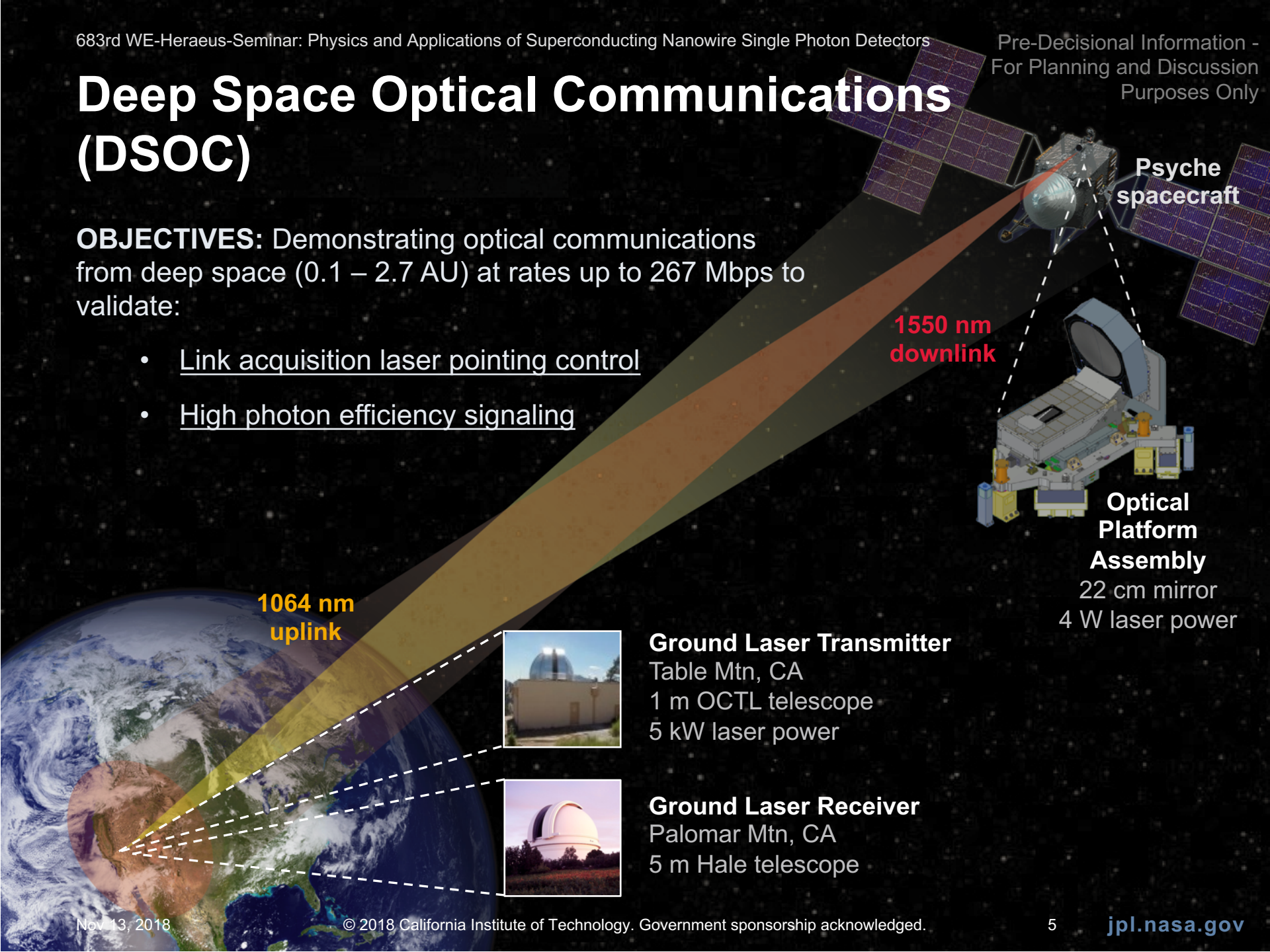- The maximum Earth-spacecraft distance will be 2.77 AU

Orbiting Psyche
for 21 Months

Arrival at Psyche
January 2026

Asteroid Psyche

Gravity Assist
May 2023

End of Mission
October 2027

Mars

Mercury

Venus

Sun

Earth

Satellite

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Deep Space Optical Communications (DSOC)

OBJECTIVES: Demonstrating optical communications from deep space (0.1 – 2.7 AU) at rates up to 267 Mbps to validate:

- Link acquisition laser pointing control

- High photon efficiency signaling

Psyche spacecraft

1550 nm downlink

Optical Platform Assembly
22 cm mirror
4 W laser power

1064 nm uplink

Ground Laser Transmitter
Table Mtn, CA
1 m OCTL telescope
5 kW laser power

Ground Laser Receiver
Palomar Mtn, CA
5 m Hale telescope

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Deep space challenges

Earth as seen from the moon during the Apollo 11 mission

← Earth

Earth as seen from Mars by the Curiosity rover

- **DSOC key challenge - huge increase in link distance from LLCD** ($90 \times$ to $> 900\times$)

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Deep space challenges

Maximum spot size (spacecraft / Earth distance = 2.77 AU)

Earth
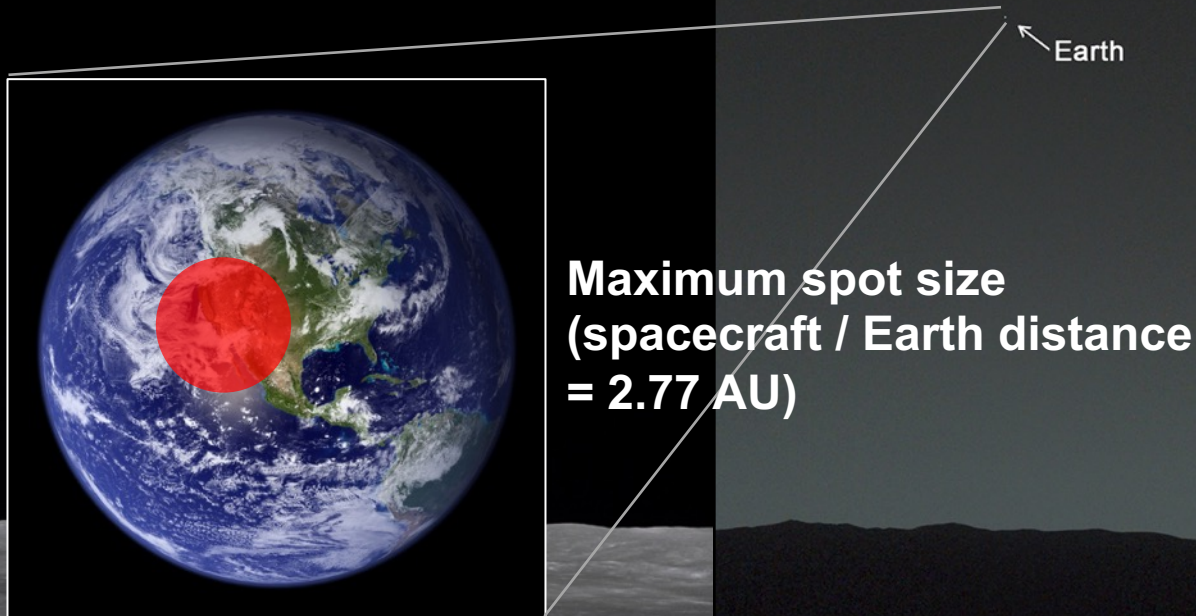
- **DSOC key challenge - huge increase in link distance from LLCD** (90 × to > 900×)
  - Increase transmitter laser power (4 W vs. LLCD 0.5 W)
  - Decrease beam divergence (8 µrad vs. LLCD 16 µrad): **introduces pointing challenge**
  - Increase flight and ground detector sensitivity

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Increasing receiver sensitivity: High photon efficiency signaling

- **High peak-to-average power ratio (160:1)**

- **Pulse-position-modulation (PPM)** with variable orders (M = 16, 32, 64, 128; Ts = 0.5,1,2,4,8 ns)

- **Near-channel-capacity forward error correction**: serially concatenated convolutionally coded PPM (SC-PPM) with variable code rates (1/3, ½, 2/3)

- **Interleaving for fading mitigation**: convolutional channel interleaver

  - Distributes deep fades across codewords to allow decoder to work (~3 dB recovered)

  - Designed with 2.7 sec depth for all data rates (based on pointing jitter estimates)

- **Lower data rates for far ranges** with variable symbol repeat factors and slot-widths (0.5 - 8 ns) – enable multitude of rates

Pulse-position modulation (PPM)

Ts

guard slots   *guard slots*

M-PPM symbol   *M-PPM symbol*   …
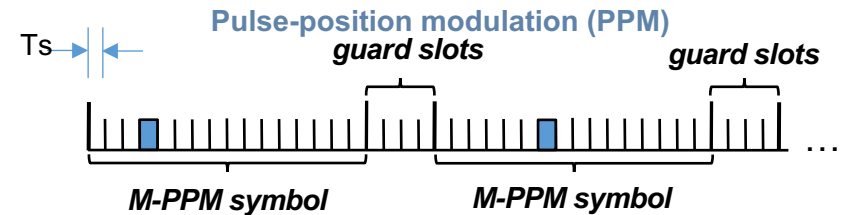
Fading causes burst outages

**Decoder corrects more errors spread across codewords by interleaver**
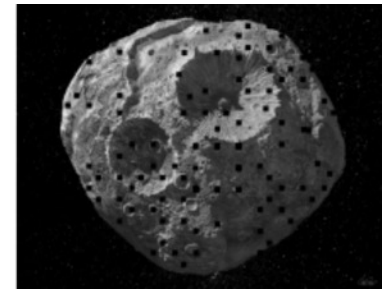
Increasing receiver sensitivity: collection area
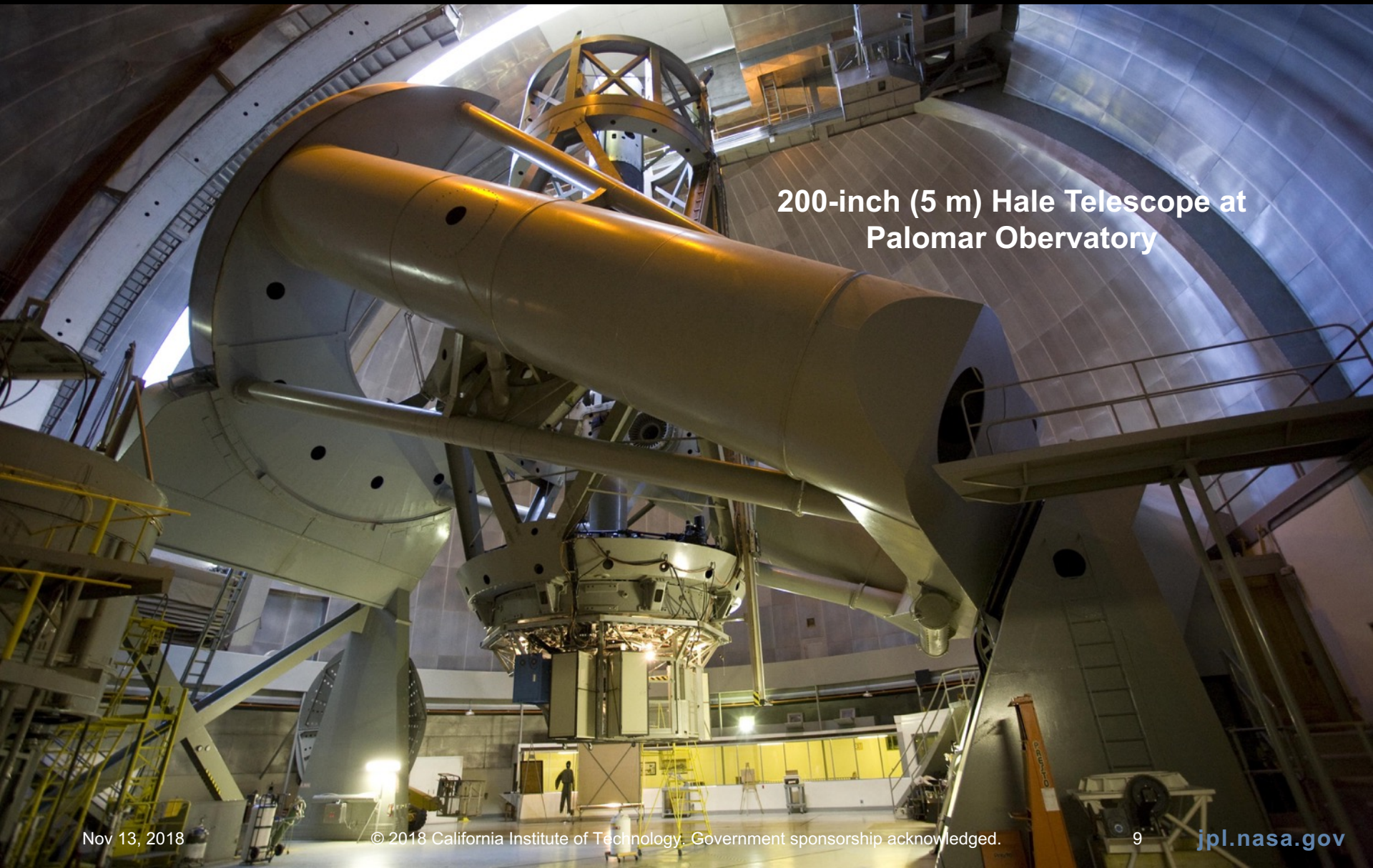
**200-inch (5 m) Hale Telescope at Palomar Obervatory**

Accommodation at Palomar Observatory

- Cryogenic detector instrument planned for Coude focus of Hale telescope
- Does not require cryostat to move with the telescope

THE TWO HVNDRED INCH TELESCOPE

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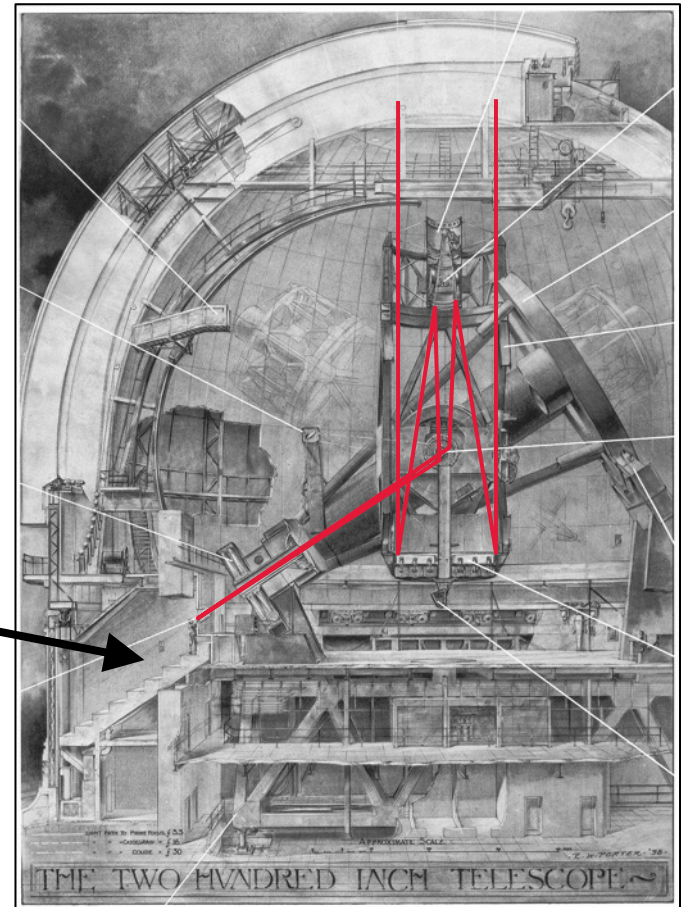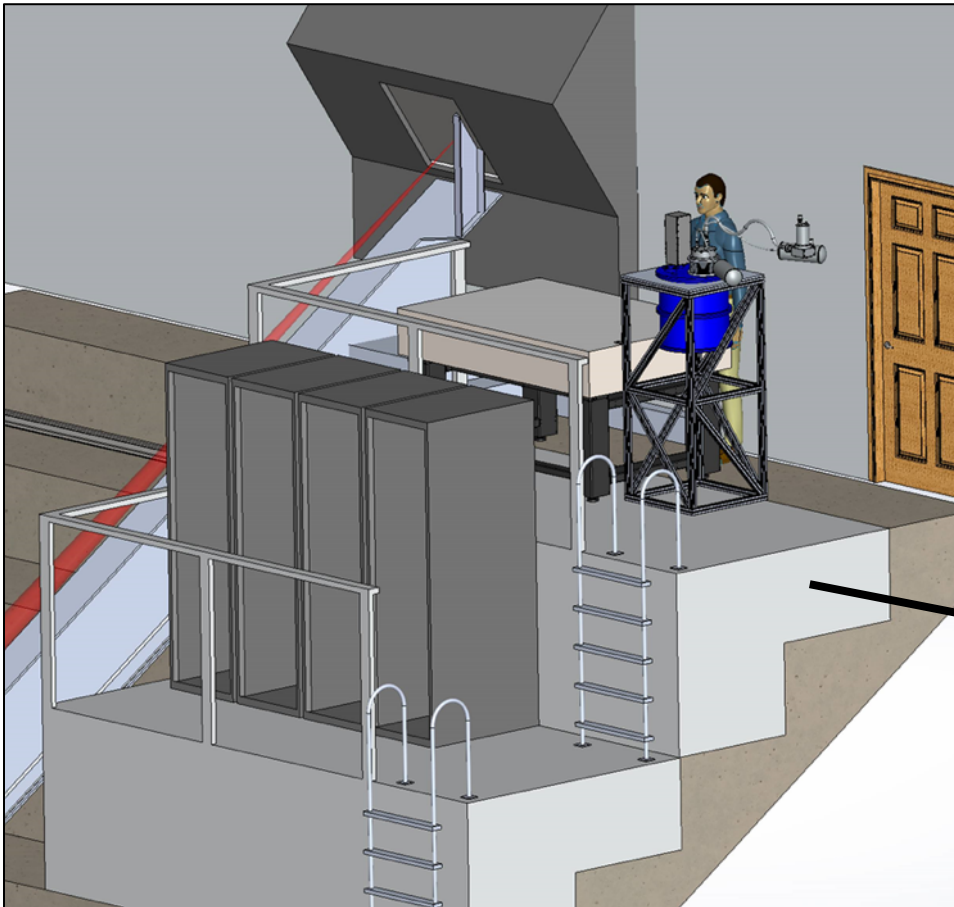
Ground receiver array design

- 64-element WSi SNSPD array with >79,000 μm^2 area (equiv. to 318.5 µm diameter)

- Divided into four spatial quadrants for fast beam centroiding

- 160 nm WSi nanowires on 1200 nm pitch; each wire ~1 mm in length (~7000 squares)

- Free-space coupling to 1 Kelvin cryostat, with cryogenic filters and lens

- 78% system detection efficiency at 1550 nm

- < 80 ps FWHM timing jitter

- ~1.2 Gcps maximum count rate

Typical fiber-coupled single-pixel active area

329 µm

269 µm

320 µm
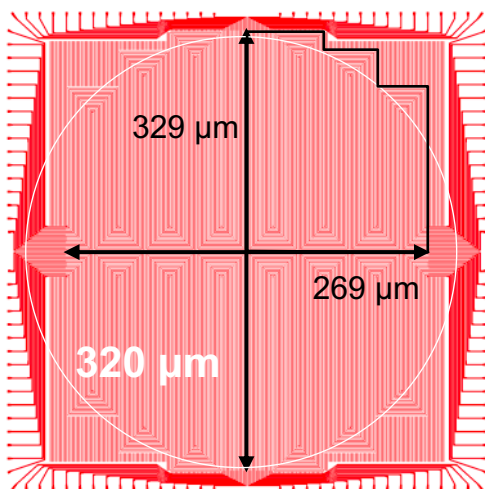
CAD Design of SNSPD focal plane array
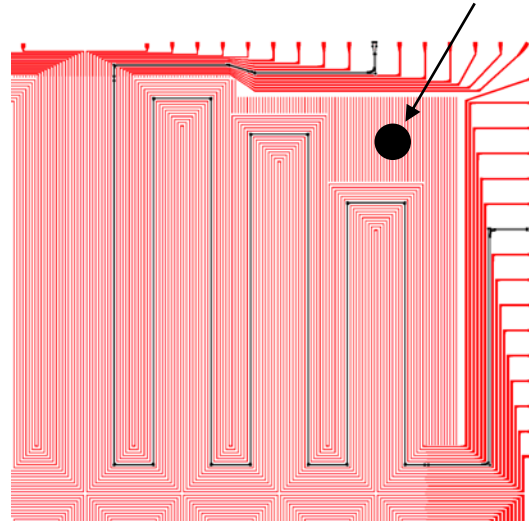
CAD Design showing one of 16 individual sensor elements per quadrant
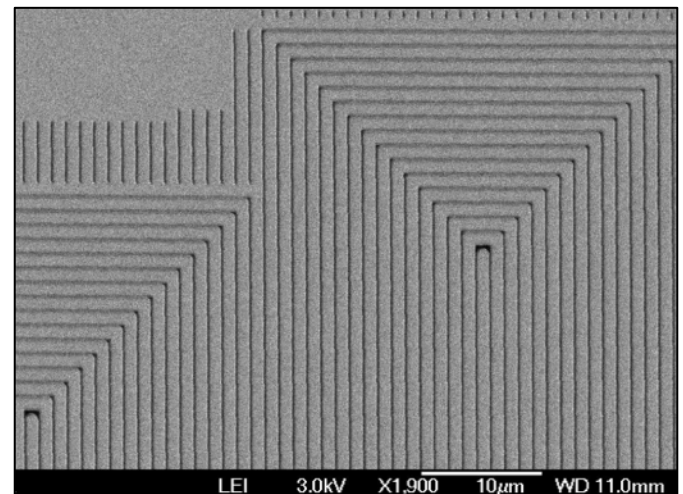
Electron Microscope Image of Nanowire Structure
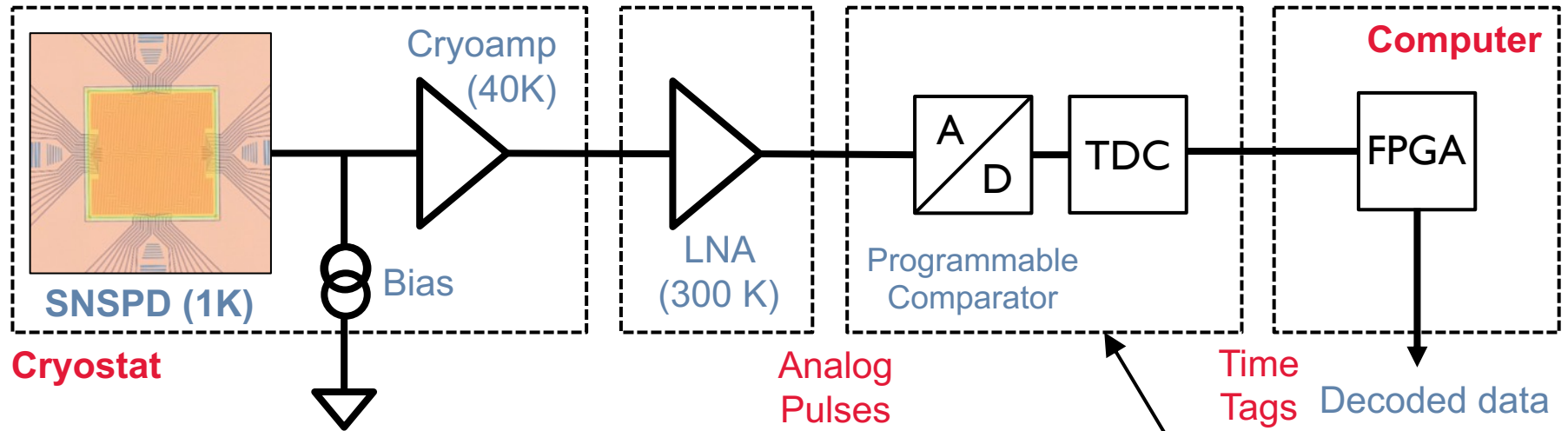
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Ground receiver readout electronics

- Each nanowire sensor element has its own dedicated readout channel

- DC-coupled cryogenic amplifiers at 40 K stage of cryostat

- Custom 64-channel TDC from Dotfast Consulting

  - Time tags are streamed over PCIe at rates up to 900 MTags/s

  - TDC has 64-channel comparator front-end

 - Time tags from all channels are sorted before streaming
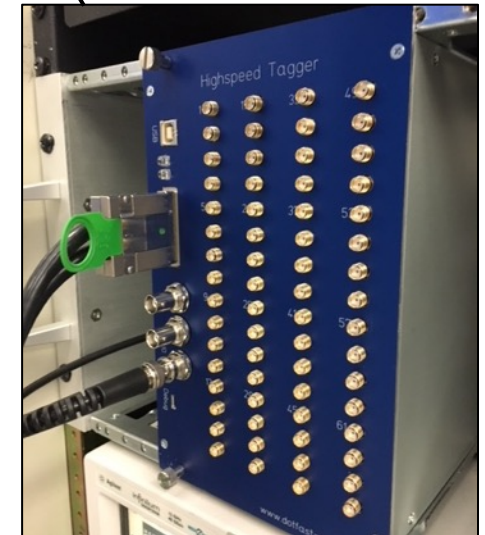
System detection efficiency

- 78% System Detection Efficiency in TE Polarization, 68% in TM. (+/- 5% uncertainty)

  - Defined as percent of photons incident on the cryostat window that are registered by the TDC.

- Measured at low flux (~100 kcps) with lens outside the cryostat (f/4 beam)

- Measured with ~230 μm diameter spot in center of array

- Prototype array has 62 out of 64 pixels working – screening arrays to find 64 perfect wires

Free-space coupling into cryostat
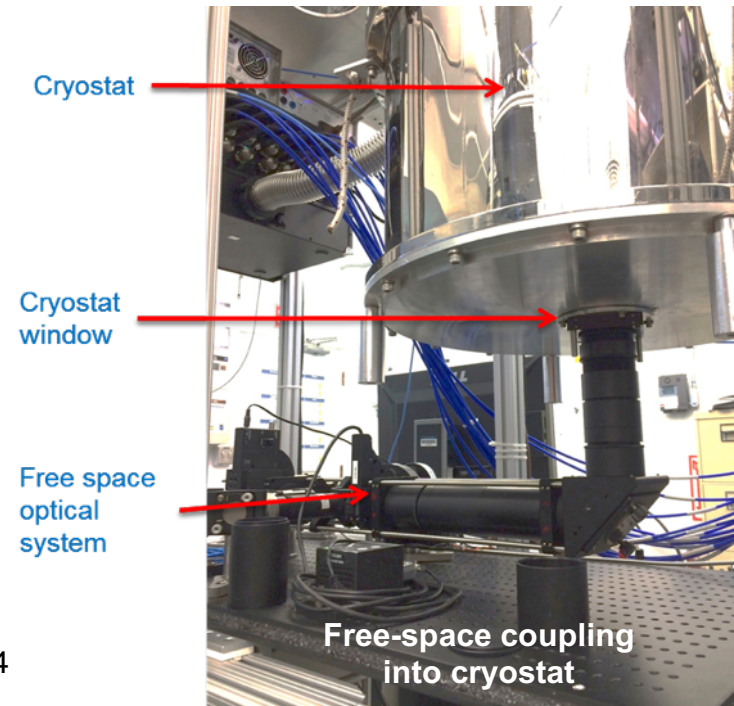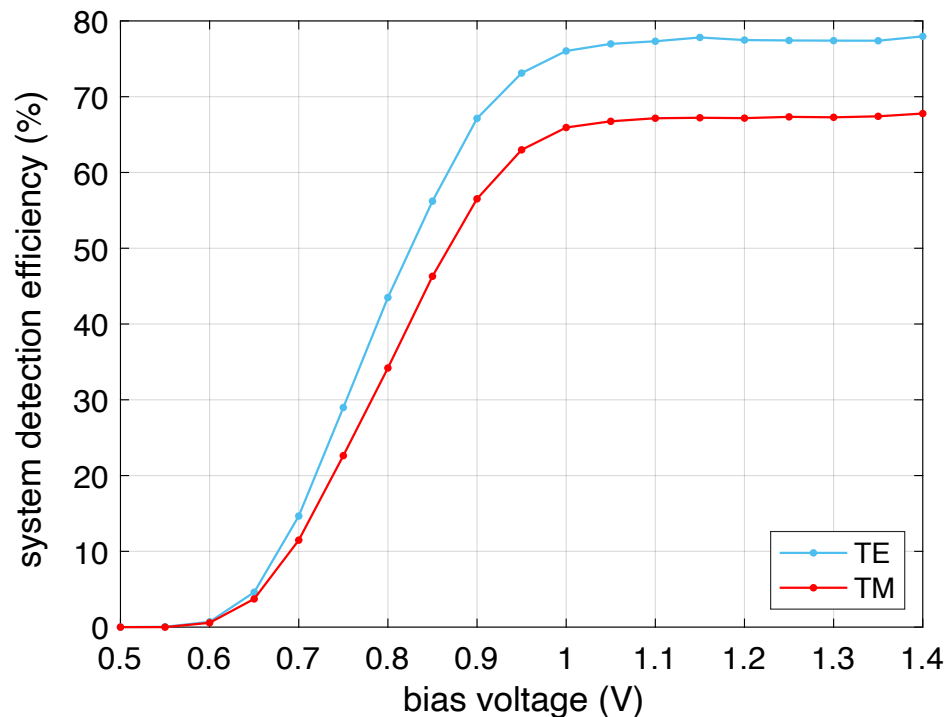
Efficiency as a function of spot size

- Used nanowire layout to estimate efficiency dependence on spot size for TE polarized light
- Optimal spot size is between 90 – 250 μm
- Small spot sizes sample bends and horizontal nanowire regions
- Large spot sizes are vignetted by the edges of the detector
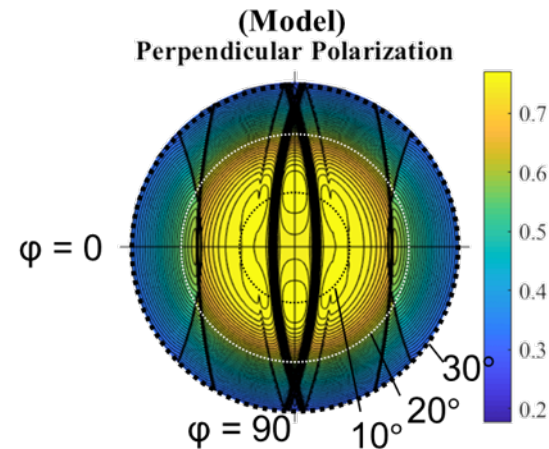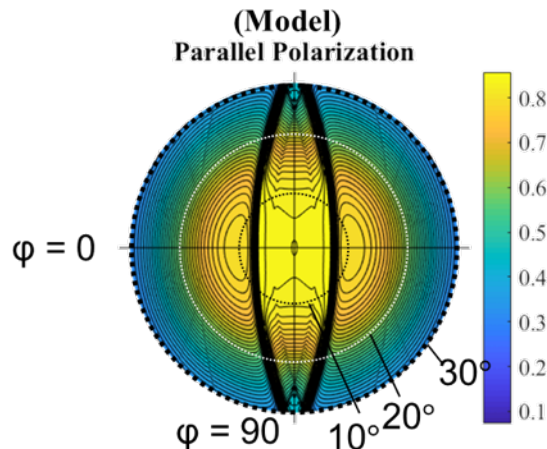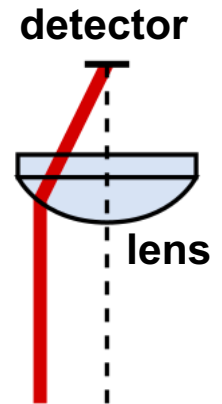- Such models can be used to perform real-time estimates of spot size with non-imaging array
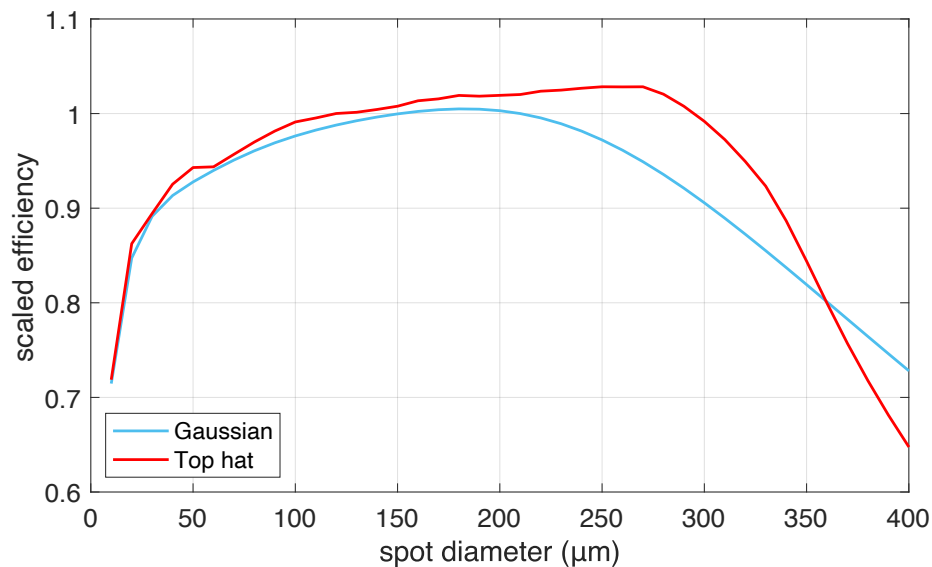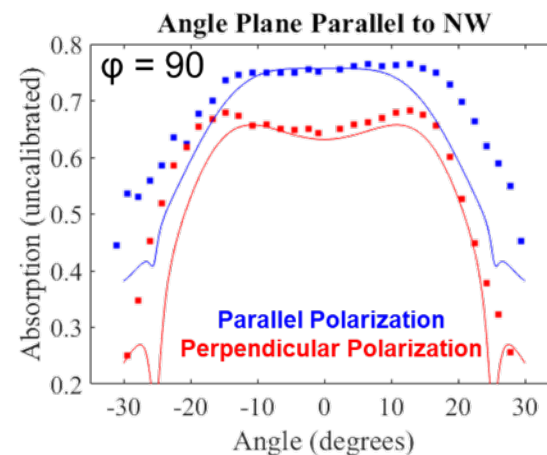

Modeled efficiency derating as a function of spot size
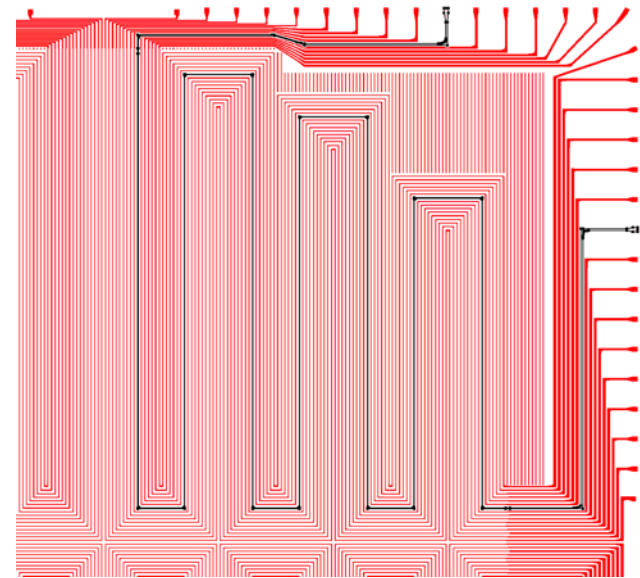
Layout of SNSPD array

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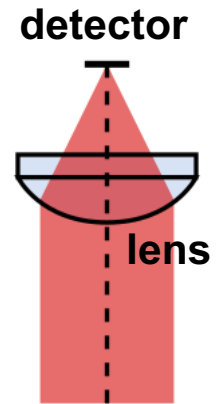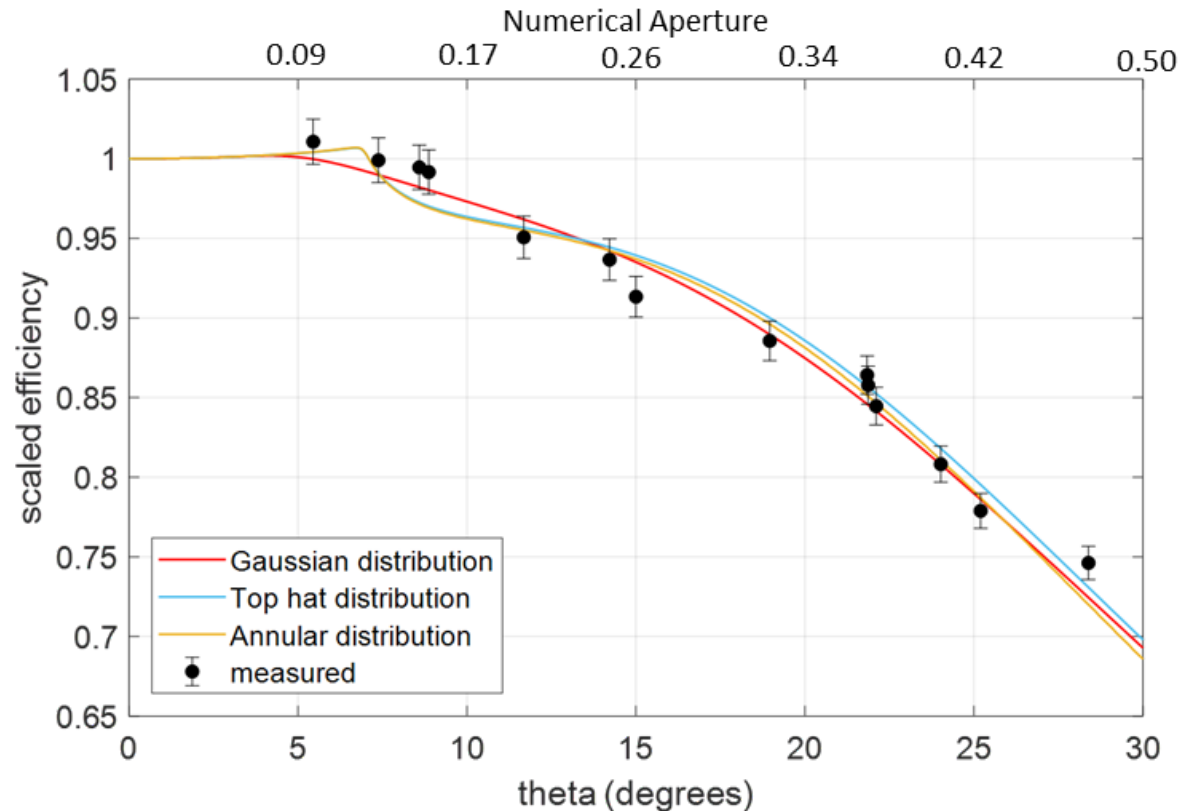
Angular efficiency dependence
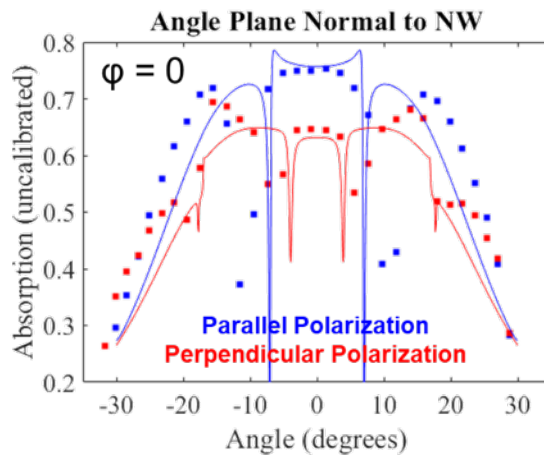
- On-chip cavity structure limits angular acceptance of detector beyond ~20 degrees
- Measured by displacing narrow collimated beam across a cryogenic lens
- Experiments show excellent agreement with RCWA simulations
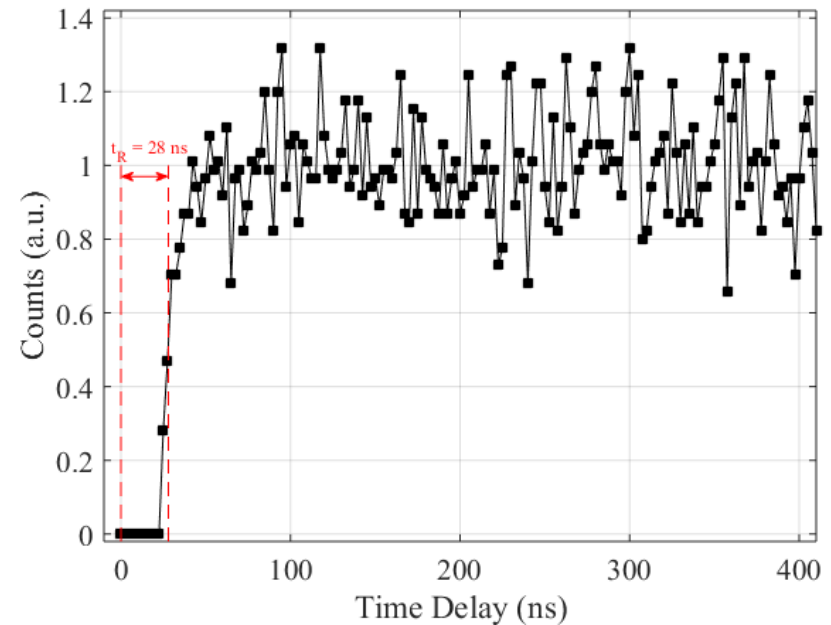
Angular efficiency dependence

- Limited angular acceptance determines finite numerical aperture of SNSPD

- 10% drop in efficiency at 0.32 NA, >20% drop at 0.42 NA

- Tradeoff in cavity design between collimated beam efficiency and angular acceptance

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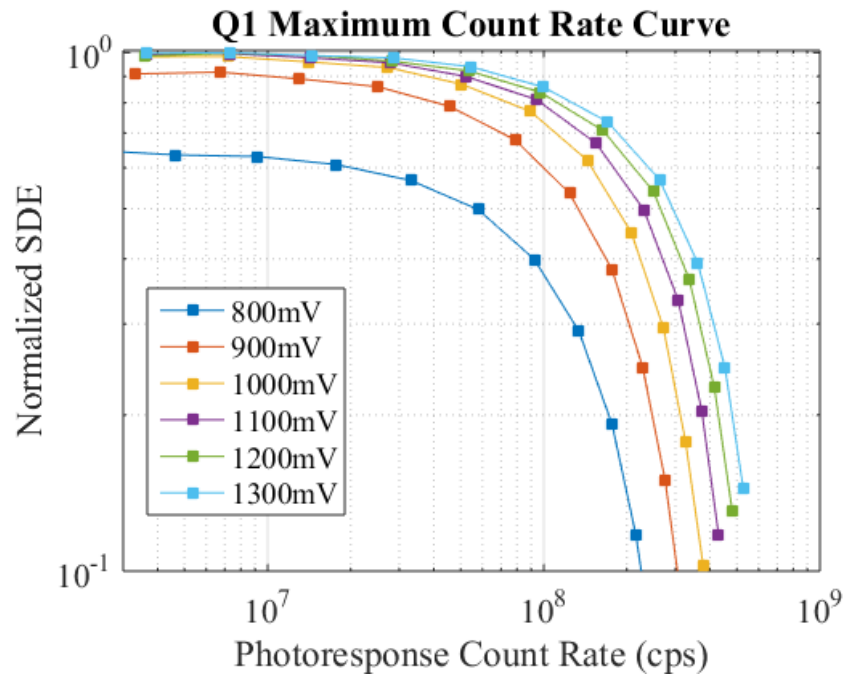
Maximum count rate

Maximum count rate measured for one 16-channel quadrant

**Interarrival time histogram showing 28 ns dead time, no afterpulsing**

- MCR measured with beam centered on a single quadrant due to count rate limitations in TDC
- 120 – 300 Mcps 3dB point per quadrant
- Scales to 465 – 1160 Mcps across 62 pixels
- Present total counting rate is limited to 900 Mcps by time tagging electronics

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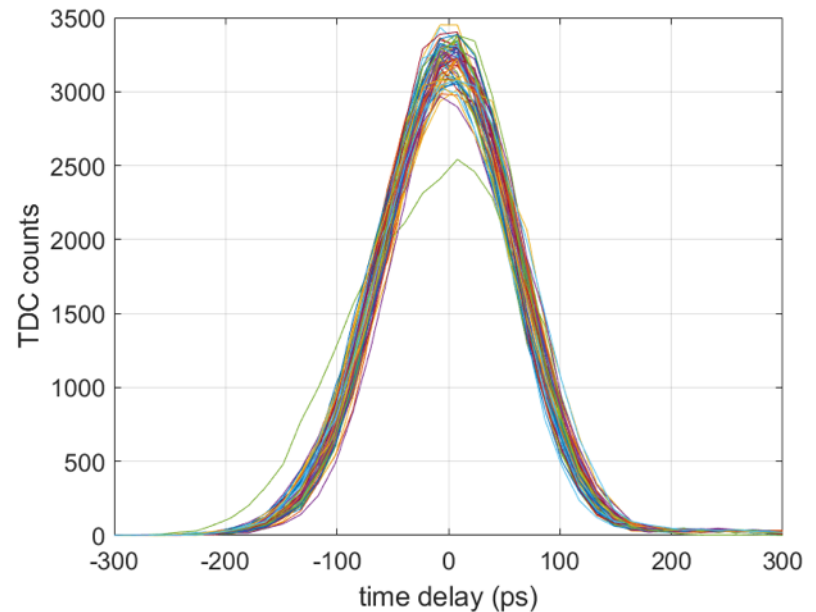
MCR as a function of signaling format
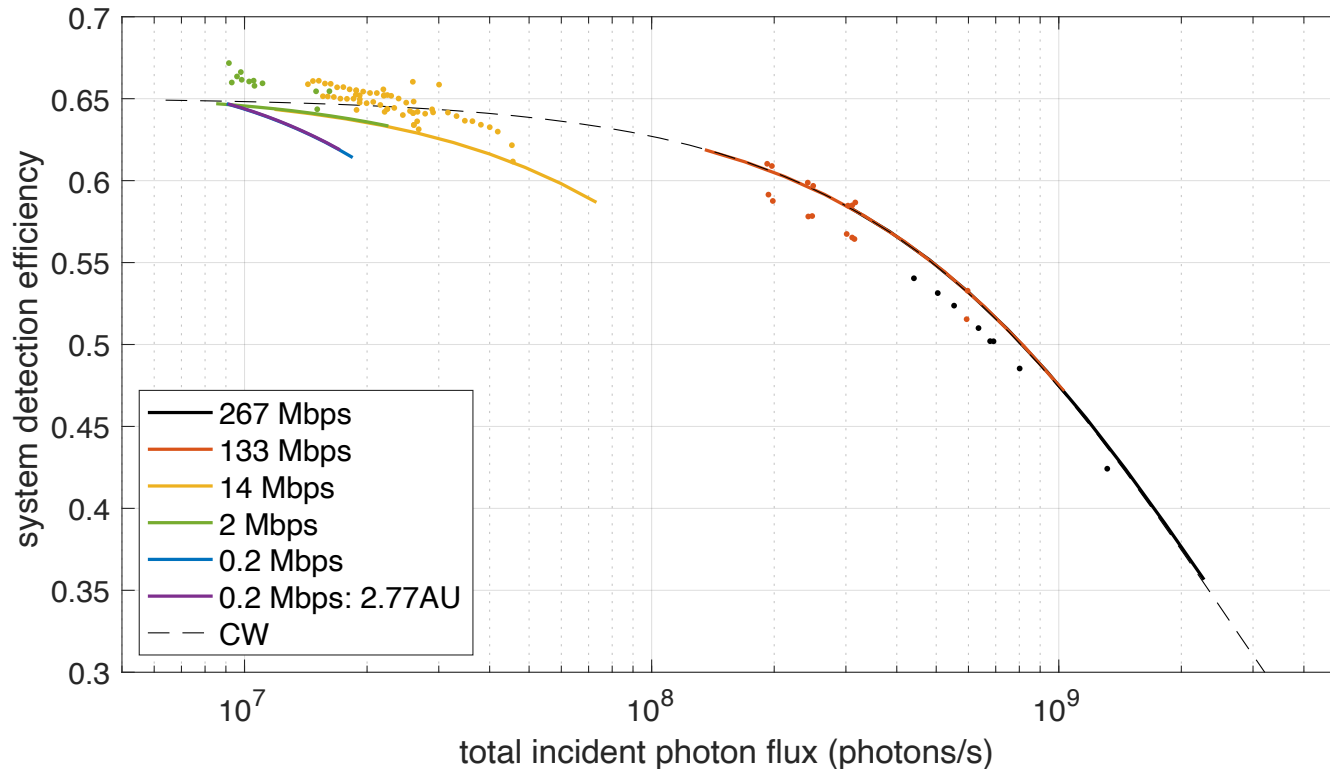
- Because each pixel can only count as fast as the signaling rep rate, MCR scales differently for different PPM data formats

- Data is for PPM-encoded communication links, scaled for expected efficiency in DSOC

Timing jitter of SNSPD and TDC
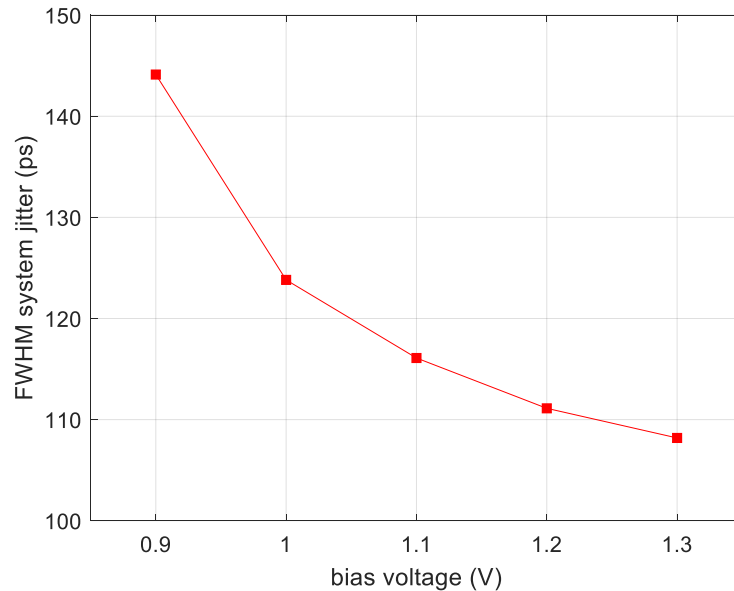

System jitter vs. bias voltage

**Instrument response function for each pixel, histogram of TDC time tags**

- Total system jitter < 120 ps FWHM at low flux rates.
- TDC jitter alone < 80 ps (approx. half of total jitter)
- Jitter expected to improve with next iteration of electronics design

Walk-induced jitter

- At higher count rates, it is more likely that the detector will fire before current has completely returned to the nanowire, producing smaller pulses.

- With a fixed threshold comparator, different pulse heights result in different time delay offsets (walk).

- Without compensation, walk increases overall jitter.
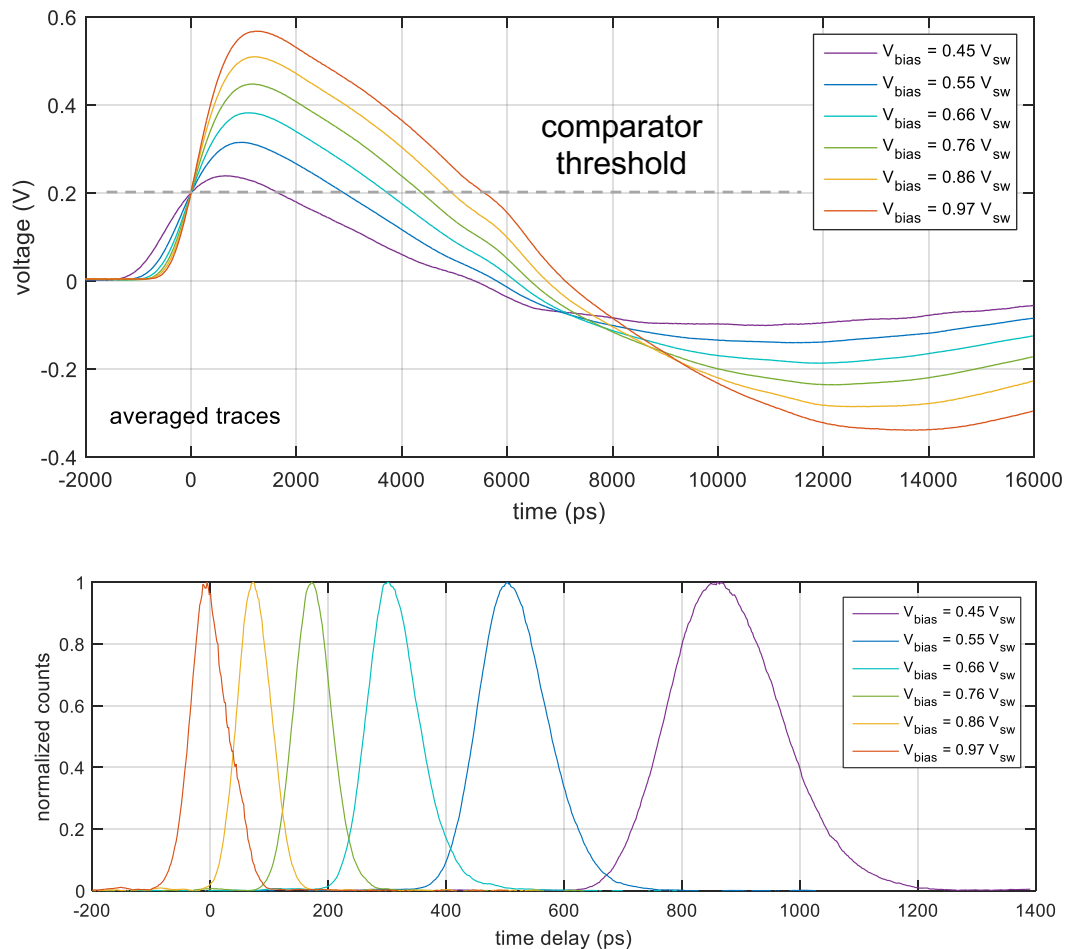
Walk-induced jitter
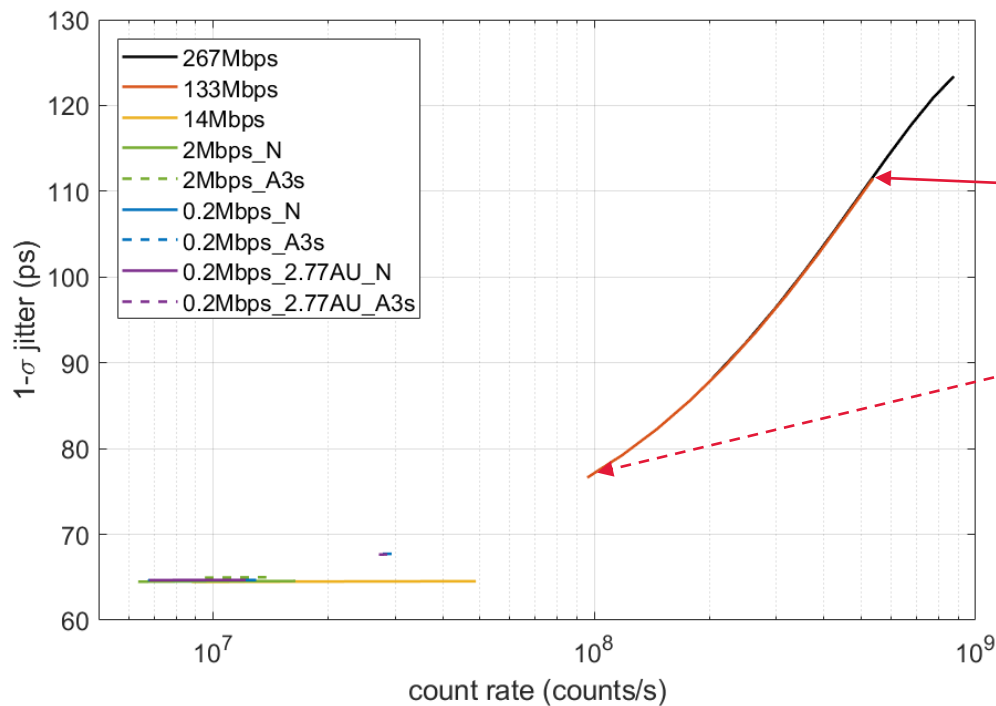
Estimated timing jitter as a function of count rate for different signaling formats
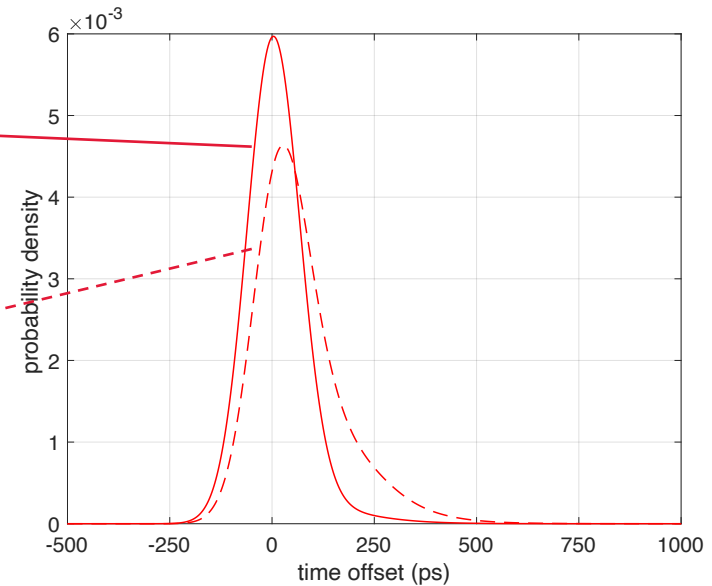
Modeled IRFs for different fluxes at a 133 Mbps data rate

- We can model the distribution of bias currents during photon absorption events for different signaling formats and predict the resulting jitter.
- Even at the highest rates, the system jitter meets our 125 ps requirement.
- For future SNSPD receivers, a constant fraction discriminator should be used to eliminate walk.

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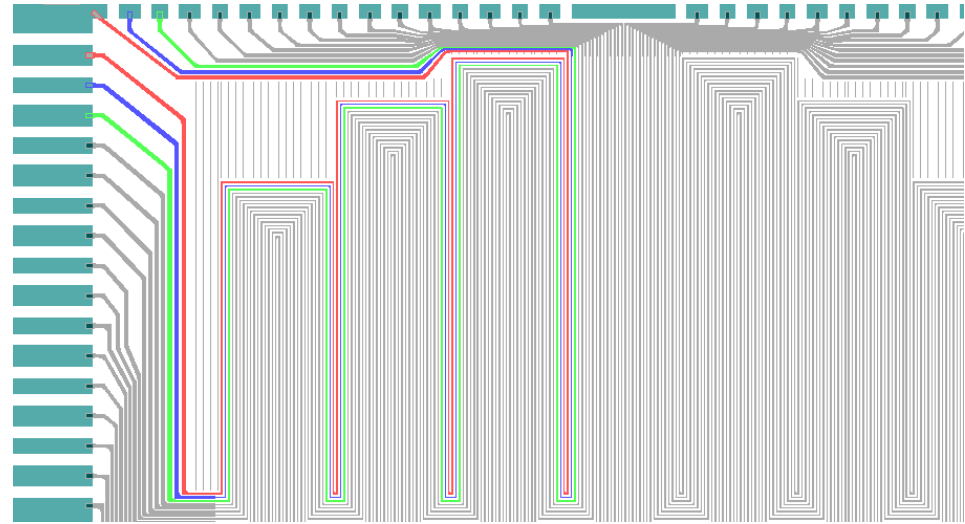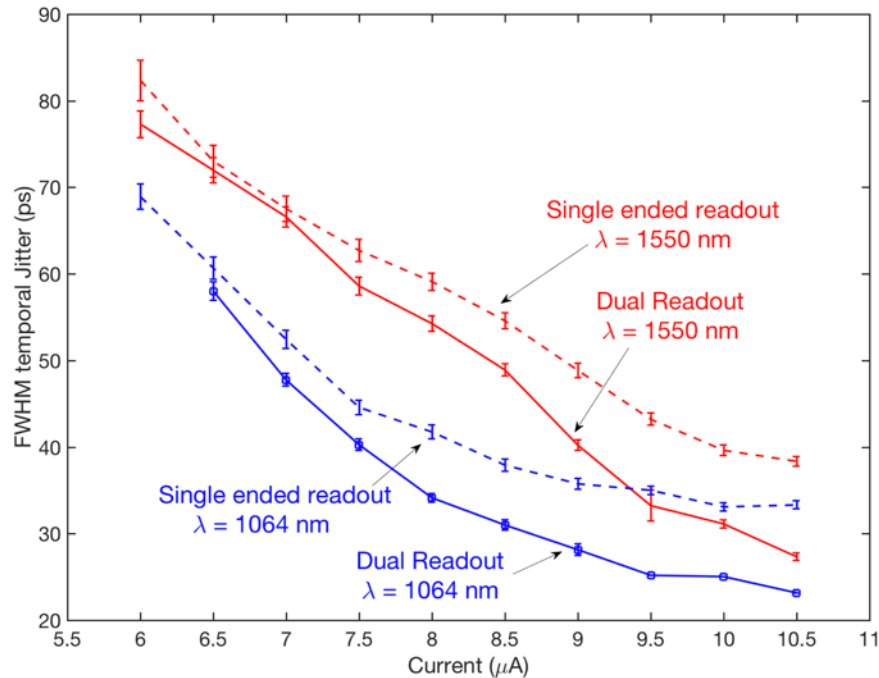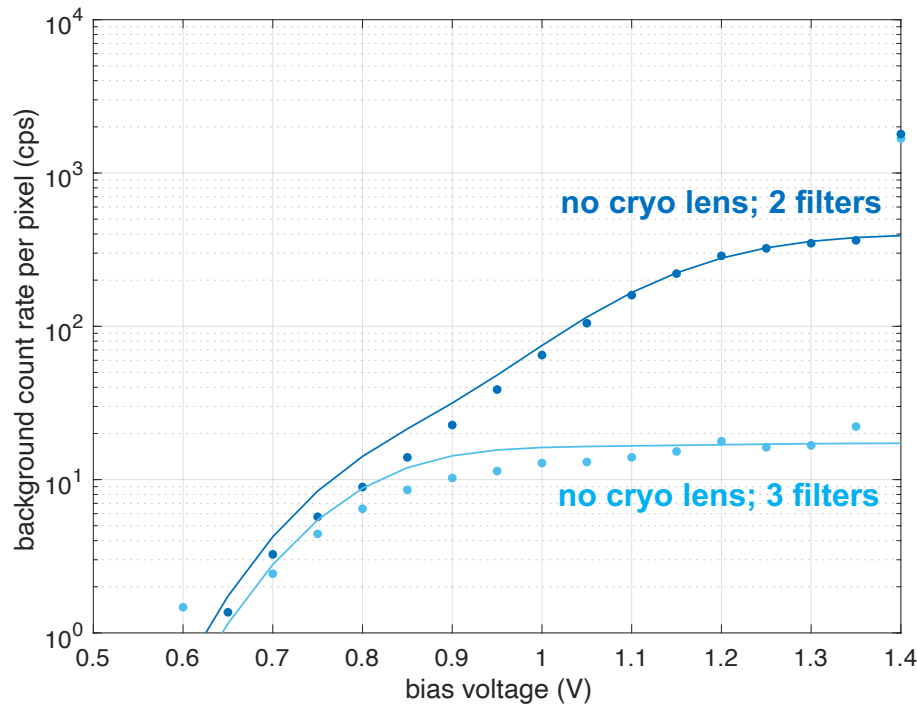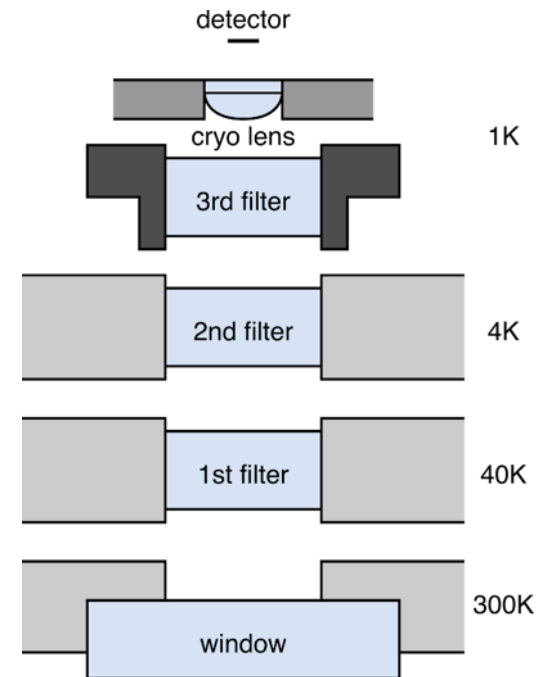
Intrinsic Limits of Timing Jitter

Illustration of differential version of DSOC-sized array

- Using a low-noise cryogenic amplifier and differential readout, demonstrated jitter < 30 ps FWHM in a WSi device similar to the DSOC array

- Photon energy dependence shows significant effect of intrinisic jitter in WSi nanowires

Dark count rate

System false count rate with model

Schematic of cryogenic filter setup

- Dark count rate is dominated by IR blackbody radiation from 300K (DCR w/ 4K window blocked is ~ 1 cps across array)

- Reflective filters on BK7 substrates at 40K and 4K are used to block 300K radiation

- ~1000 cps false count rate across array with lens outside cryostat (16 cps per pixel)

- Expect ~10 kcps across array with increased FOV of cryogenic lens

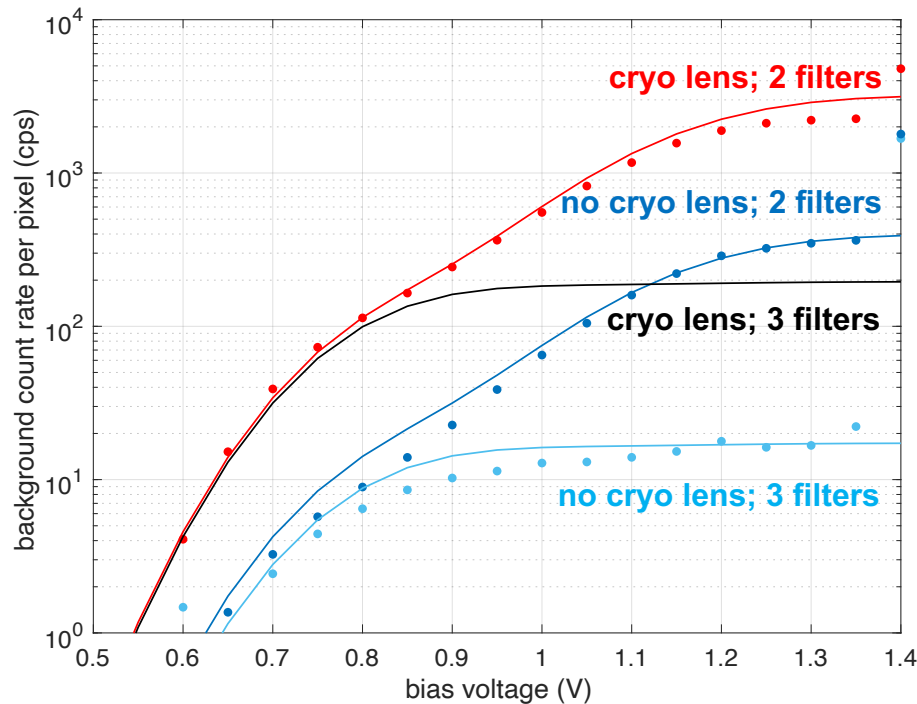**jpl.nasa.gov**

Dark count rate
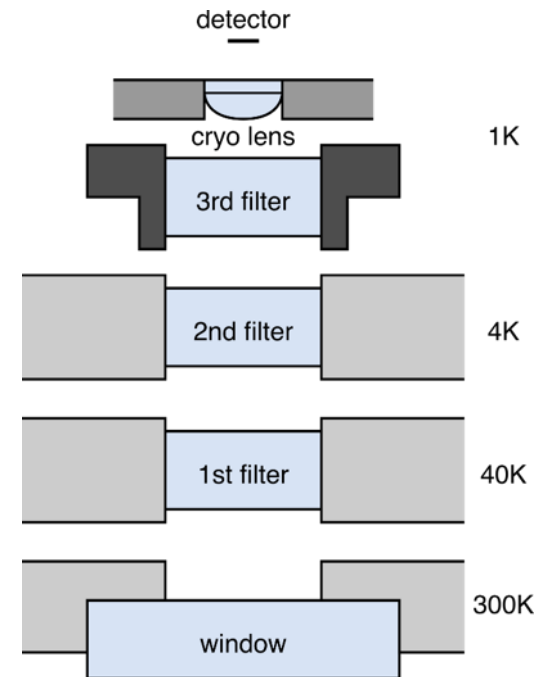
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End-to-end testing

- To test the performance of the ground receiver system, we can send data with a fiber-coupled modulated laser into the free-space optics.

- Initial round of end-to-end tests **closed links** at data rates from 0.2 Mbps to 267 Mbps under realistic signal and background fluxes.

- Examples of tests:
  - Link budget verification
  - Functionality of interleaver in the presence of fading
  - Error rate as spot is moved off of array
 - Effect of clock drift
  - Slot synchronization
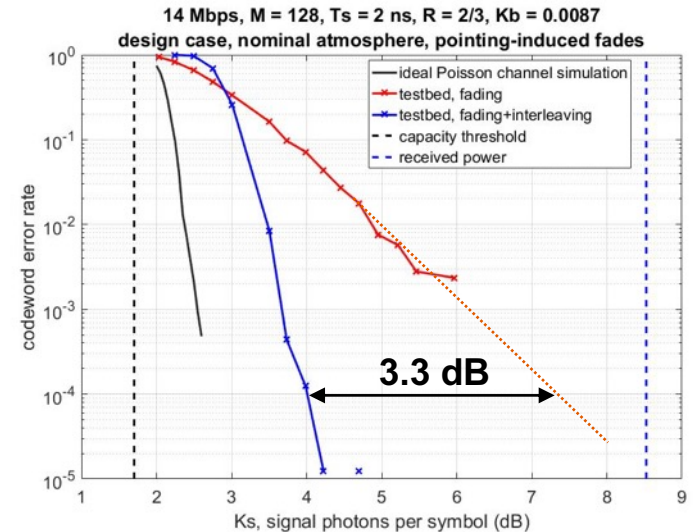
Error rate vs. flux w/ and w/o interleaving
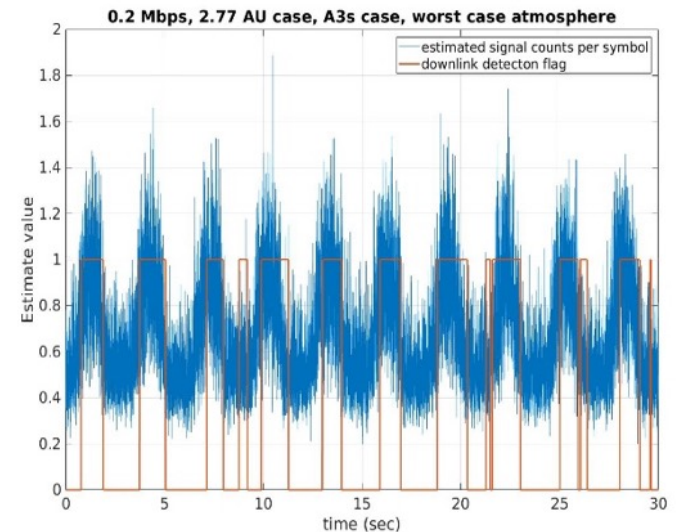
Signal counts and detection flag from the receiver as beam is swept across array

Current status

- Designing cryostat for Palomar Coude room
- Optimizing initial optics and electronics designs now that array is fully characterized
- Screening dies to identify best device and back-ups
- Improving end-to-end testing to make conditions as faithful to those in DSOC as possible

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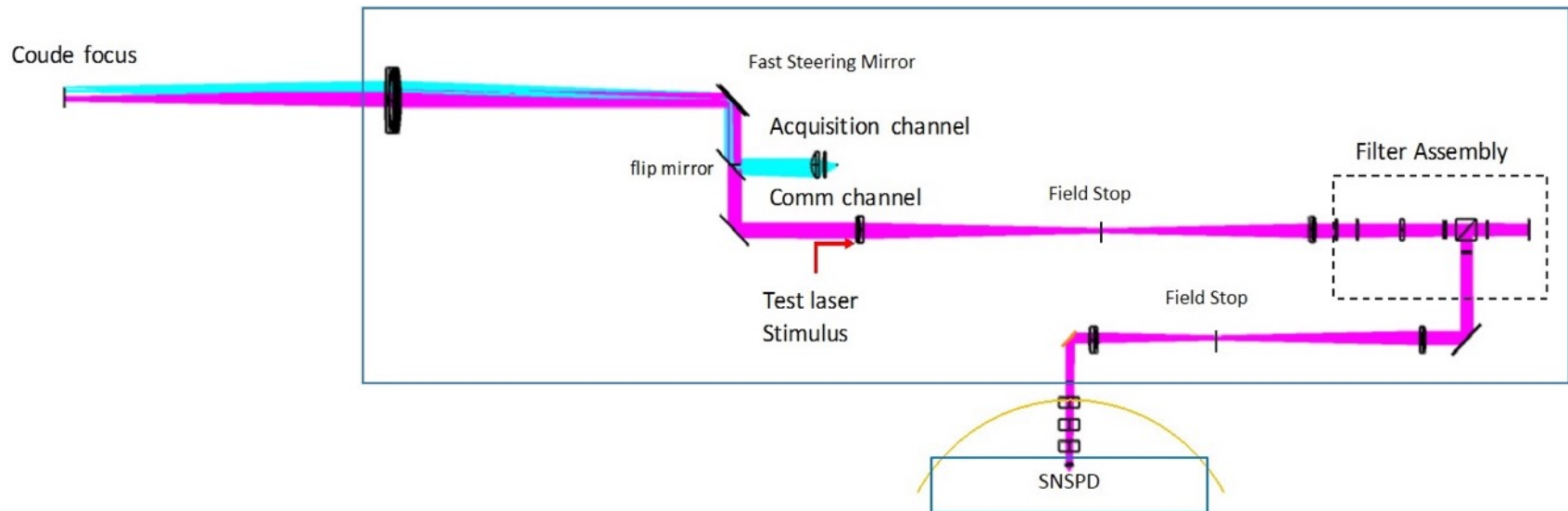
Summary and Future Directions

- Deep space laser communication offers 10-100x higher data rates than Ka-band radio for equivalent mass and power on the spacecraft

- NASA DSOC project will provide the first demonstration of laser communication from beyond lunar orbit, with free-space links up to ~400 million km

- 64-pixel SNSPD arrays are a key technology for the ground receiver at Palomar observatory

- Future optical Deep Space Network will require ~10x larger and faster SNSPD arrays
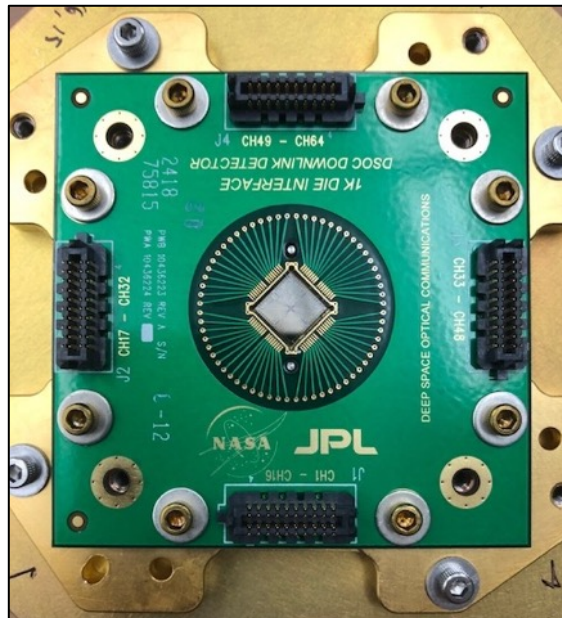
Packaged SNSPD Array
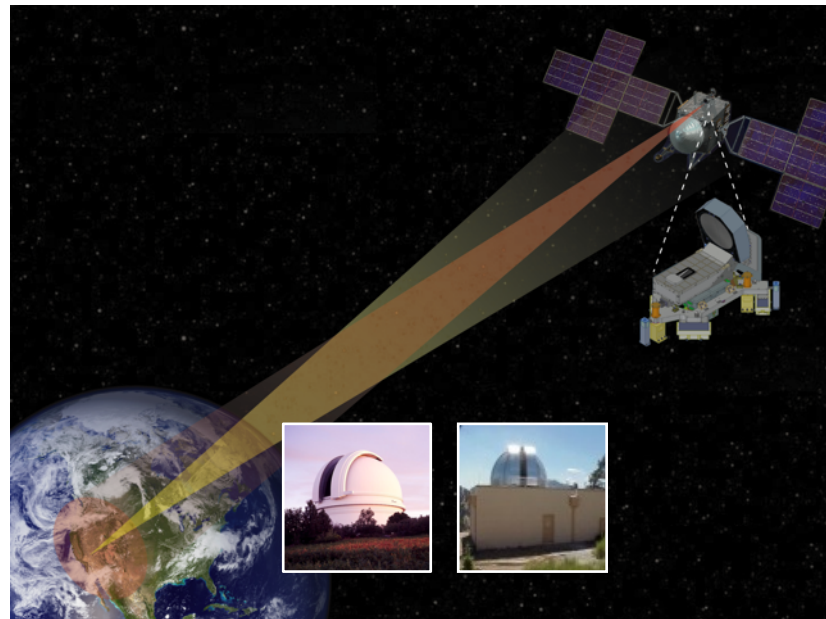
DSOC Project Concept

JPL SNSPD development team

JPL Staff

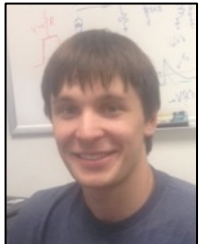Matt Shaw Andrew Beyer Ryan Briggs Emma Wollman Marc Runyan Angel Velasco
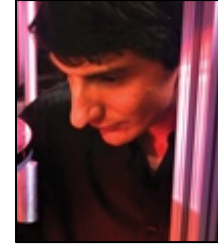
Postdocs ## Graduate Students ## Alumni

Boris Korzh Jason Allmaras Andrew Mueller Jeff Stern 1962-2013 Francesco Marsili Bill Farr

Visiting Students

Edward Ramirez

Simone Frasca   Misael Caloz
Eric Bersin   Megha Tippur
Kelly Cantwell   Garrison Crouch
Chantel Flores   Andrew Dane
Sarang Mittal   Emerson Viera
Marco Suriano   Viera Crosignani
Luca Marsiglio   Michael Mancinelli
Giovanni Resta   Neelay Fruitwala
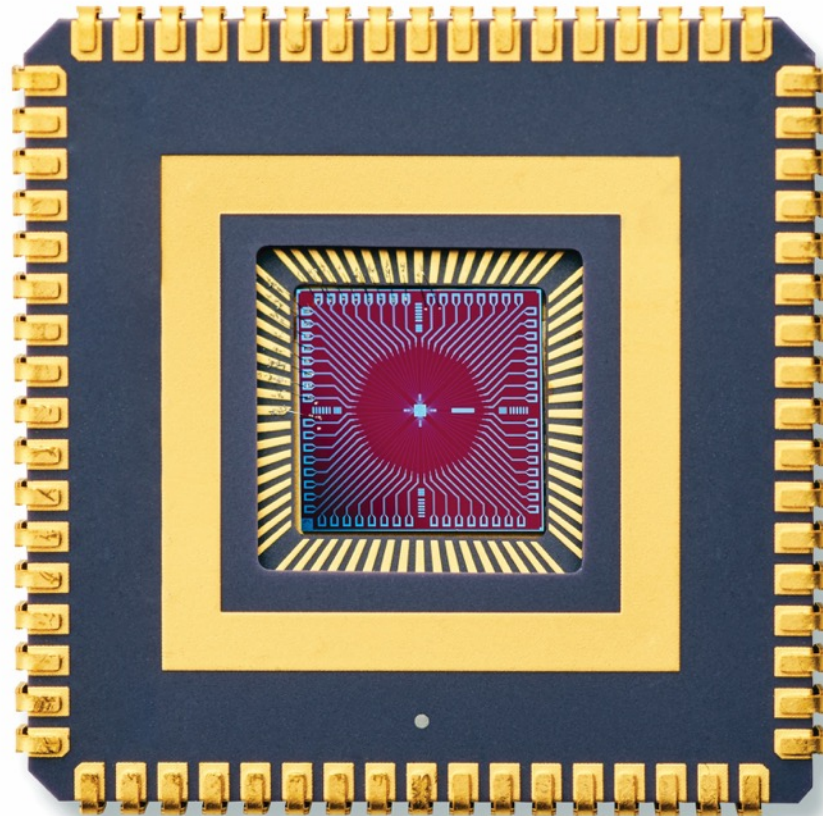
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Ground receiver readout electronics
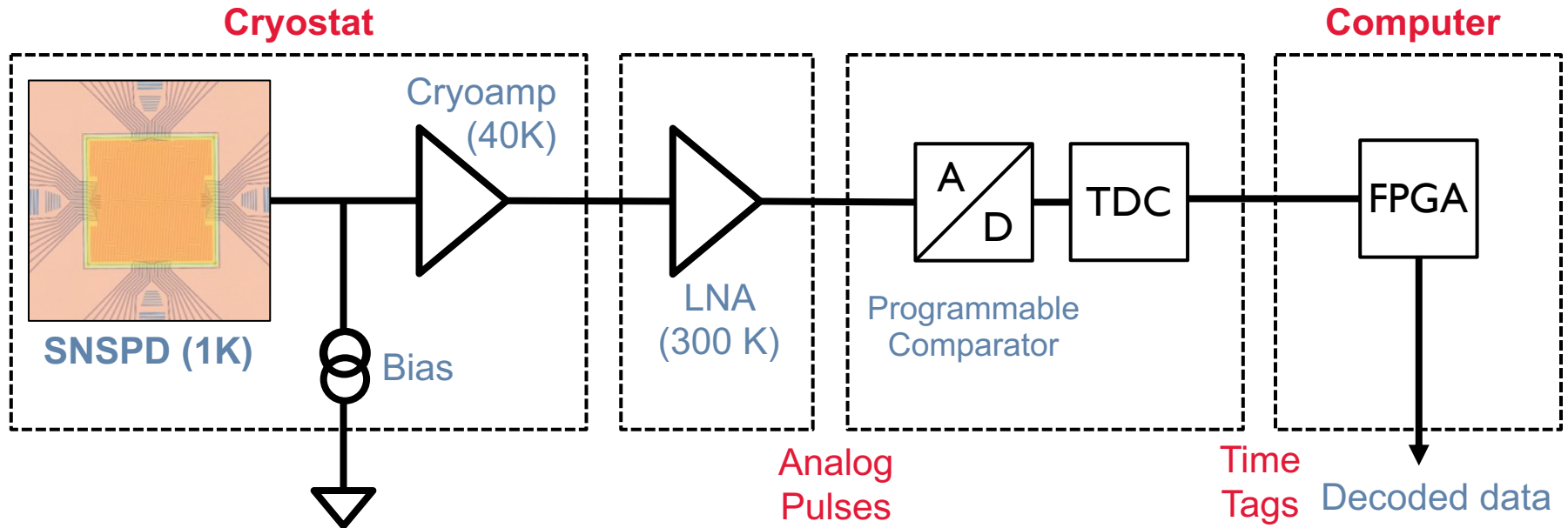
Cryostat

Computer

Cryoamp
(40K)

SNSPD (1K)   Bias

LNA
(300 K)

A/D

TDC

FPGA

Programmable
Comparator

Analog
Pulses

Time
Tags   Decoded data

- Each nanowire sensor element has its own dedicated readout channel
- DC-coupled cryogenic amplifiers used at 40 K stage of cryostat
- Custom 64-channel TDC from Dotfast Consulting
  - Time tags are streamed over PCIe at rates up to 900 MTags/s
  - TDC has 64-channel comparator front-end
  - Time tags across all channels are sorted before streaming

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Efficiency vs. channel

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